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Human Factors in Aircraft Maintenance

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Abstract: Human error is cited as a major causal factor in most aviation mishaps, including the 15% - 20% that involve maintenance error. Errors can be described as active failures that lead directly to the incident, and latent failures whose presence provokes the active failure. Typical aviation maintenance errors are presented as examples and two approaches to human error reduction given: incident based and task analysis based. Each approach provides data on performance shaping factors, i.e. situation variables that affect the probability of error occurrences. Examples are given of interventions derived from analysis of incidents and from task analysis.

1. The Need for Human Factors in Maintenance: A sound aircraft inspection and maintenance system is important in order to provide the public with a continuing safe, reliable air transportation system (FAA, 1993). This system is a complex one with many interrelated human and machine components. Its linchpin, however, is the human. While research and development related to human factors in aviation has typically focused on the pilot and the cockpit working environment, there have been maintenance initiatives. Under the auspices of the National Plan for Aviation Human Factors, the FAA has recognized the importance of the role of the human in aircraft safety, focusing research on the aircraft inspector and the aircraft maintenance technician (AMT) (FAA, 1991, 1993). The classic term, "pilot error" or "human error", is attributed to accidents or incidents over 75% of the time; however, a recent study in the United States found that 18% of all accidents indicate maintenance factors as a contributing agent (Phillips, 1994).

Two incidents help clarify the issues involved and demonstrate that even though humans in the system were trying to do a good job, systems problems combined with errors to allow a serious event.

> *Case 1: Lockheed L-1011.* An in-flight turn-around was caused by all three engines failing on a flight from the USA to the Caribbean when the oil leaked out of each. The oil leak was caused by missing "O" rings on the magnetic chip detectors. They were missing because the mechanic had not notices that the new chip detectors were not fitted with "O" rings in the usual way. All work was performed outside in darkness, where a black "O" ring was difficult to see. Until that night, chip detectors had always come with "O" rings attached, even though the mechanic had to sign for both components. The new packaging still said they were ready for use.

> *Case 2: BAC-111.* During industrial action at the airline, a maintenance manager changed a windshield himself. He had not performed this task for two years, but checked the Maintenance Manual and it looked straightforward. He replaced 80 of the 84 bolts. The correct bolts were A211-8D, although A211-7D were on the old windshield. He matched the old bolts to new ones in a stores bin, but chose A211-8C, which was the correct length but the wrong thread. They engaged in the holes, but he used the wrong torque in setting them. Also because of the awkward posture required he could not see the bolts tighten. On the first flight, the windshield blew out, severely injuring the pilot and forcing an in-flight turn-around.

As a result of such incidents, the public has become more aware of the importance of aircraft maintenance as a safety issue, and both the civil aviation industry and its regulatory bodies have responded with programs to increase safety. Such programs have included hardware-based initiatives, such as the FAA's Aging Aircraft

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Program, and human factors initiatives by the FAA and many international bodies, for example by Transport Canada and the European JAA.

Over the last decade various human factors studies in maintenance-related issues have been initiated by agencies such as the FAA and NASA, by manufacturers, and by the aircraft maintenance industry. Examples of these initiatives are the National Aging Aircraft Research Plan (NAARP), the “Safer Skies” initiative, the White House Panel on Aviation Safety, and NASA’s aircraft maintenance program. The objective of all these has been to identify research issues and to promote and conduct both basic and applied research related to human factors in aircraft maintenance. The human factors approach in maintenance research considers the human as the center of the system. Not only can human factors research have a significant effect on the design of new systems but it can also mitigate problems found in the sub-optimal designs of current systems.

2. Human Factors Approaches to Maintenance: Clearly, the main issue in aviation from a safety viewpoint is errors, or alternatively reliability. Where humans are part of the system, errors cannot be separated from the other two aspects of humans at work: performance speed and human well-being. Performance, typically measured by both reliability and speed, is the major concern of employees. Human well-being, e.g. health and safety of the workforce, is also an employer concern but is vital to continuing human work within a system. To some extent, there are tradeoffs between speed, reliability and well-being, but any human factors changes we make to improve the human/system fit can be expected to have a beneficial impact on all three measures. For this reason, our main consideration in this paper will be error reduction, or its equivalent: reliability improvement.

Perhaps the most widely accepted error models arise from systems reliability analysis (e.g. Embrey, 1984) but in the human error field more cognitive models have gained wide acceptance. These were originally developed for tasks such as aircraft piloting, industrial process control or air traffic control (Nagel, 1988). The ideas of Reason (1990) concerning error in complex systems have been particularly influential.

Reason differentiates between the proximal cause of an accident, the Active Failure, and more hidden causes that make the accident sequence more likely, the Latent Failures or Resident Pathogens. Active failures are at the “sharp end” of the incident, for example the pilot who fails to prevent an aircraft impacting a mountain, and are thus usually discovered easily. Resident pathogens, in contrast, can lie dormant in a system for considerable periods before they become manifest. In the L-1011 example, the active failure was that “O” rings were not installed, but a number of latent failures ensured that the changed parts led to an incident:

1. The mechanic’s habituation to signing for both components even when they came as an assembled unit.
2. The dark outside environment that prevented ready detection of the error.
3. The assignment of the same mechanic to service all three engines, a practice no longer tolerated, e.g. for ETOPS certification.
4. The unchanged packaging and lack of alerting of the mechanic to the change.

In Reason’s model, if we can reduce the latent failures, then the active failure will be prevented. We try to reduce the impact of latent failures by attempting to prevent error propagation through a system, usually by providing barriers (or error traps or recovery mechanisms). Thus, in the above example, training the mechanic to check each component before signing would be a barrier to error propagation. It would be a relatively poor barrier as training people to perform unnatural acts is not particularly reliable. We characterize such a barrier as being porous. Clearly, if enough of the barriers are porous, a triggering event such as the changed packaging can propagate through several barriers to impact public safety. In aviation the aim is to provide barriers which prevent such propagation. In fact, a system that has only a single barrier is considered unsafe and thus prevents an aircraft being certified as airworthy. At times it may not be apparent from initial analyses that there is only a single barrier. The recent crash of Concorde in Paris gives such an example.

There are two complementary ways to locate resident pathogens in any system:

1. *Incident-based.* If incidents have occurred, then detailed analyses of them will list resident pathogens as well as active failures.
2. *Task-Analysis-based.* Whether or not incidents have occurred, comparison of task demands with human capabilities will locate task elements where errors are likely, i.e. resident pathogens.

Both of these approaches have been used successfully in aviation maintenance. The next two sections cover products of the FAA's Human Factors in Aviation Maintenance and Inspection Program over the past decade and provide instances of usable findings to help achieve non-porous error barriers. More comprehensive accounts can be found in the special issue of *International Journal of Industrial Ergonomics*, Volume 26(2000), 125-240, and in the *Proceedings of the IEA 2000/HFES 2000 Congress*, Volume 3, pages 766-798. Information from the FAA's program is available on-line at hfskyway.faa.gov.

3. Incident-Based Approaches: In Section 1, two incidents were presented to illustrate human factors in maintenance accidents—an incident-based approach. Similar approaches have been the analysis of all maintenance-caused accidents investigated by the National Transportation Safety Board (available on hfskyway.faa.gov) and the development of a set of prototypical unsafe behaviors, known as the "Dirty Dozen" (Dupont, 1997). The Aviation Safety Reporting System (ASRS) in the USA can also be searched for maintenance-related incidents to provide additional examples of latent as well as active failures.

Based on such listings of maintenance-related latent failures, several incident analysis schemes have been proposed. These focus at least initially on single incidents, whether the severity of the incident is an aviation catastrophe (very rare), an operational incident such as an aircraft diversion (more common) or even an error discovered before it had propagated (quite common). There is good evidence that the same latent failures are found in the path leading towards severe incidents as in paths towards incidents of less consequence (Schmidt et al, 2000). Typical incident investigation systems include the Human Factors Analysis and Classification System – HFACS (Schmidt et al, 2000), the Proactive Error Reduction System – PERS (Drury, Wenner and Murthy, 1997) and the Maintenance Error Decision Aid – MEDA (Rankin, 2000). The last of these is typical in that it was derived from applying the human reliability analysis tradition to maintenance incidents. Typical errors were used to derive Performance Shaping Factors (PSF's) which describe situational variables that affect error likelihood, such as poor training or adverse weather conditions. Hierarchical lists of such factors were developed and used to provide a 4-page checklist covering:

Error Types

- improper installation improper
- servicing, improper/incomplete repair, improper fault
- isolation/inspection/testing, actions causing foreign
- object damage, actions causing surrounding equipment
- damage, and actions causing personal injury

Contributing Factors (PSFs)

1. Information-written or computerized source information used by maintenance technicians to do their job, e.g., maintenance manuals, service bulletins, and maintenance tips
2. Equipment, tools, and parts
3. Airplane design and configuration
4. Job and task
5. Technical knowledge and skills
6. Factors affecting individual performance-e.g., physical health, fatigue, time constraints, and personal events
7. Environment and facilities
8. Organizational environment issues-e.g., quality of support from other Maintenance and Engineering organizations, company policies and processes, and work force stability

9. Leadership and supervision-e.g., planning, organizing, prioritizing, and delegating work
10. Communication-e.g., written and verbal communication between people and between organizations.

Error Prevention Strategies: existing procedures, processes, and policies in the maintenance organization that were intended to prevent the error, but did not.

Even though analysis of each investigated incident produces error prevention strategies specific to that incident, more use can be made of the accumulated data from many incidents to guide broader policies. Wenner and Drury (2000) analyzed data from 130 incidents that had resulted in ground damage to civil aircraft. These incidents, Ground Damage Incidents (GDIs), had been investigated and reported to the Technical Operations Department of an airline from 1992-1995.

Initially, each GDI report was reviewed to determine the specific action that caused the ground damage. The reports could be sorted into twelve distinct patterns covering almost all of the GDI reports, termed here as Hazard Patterns after Drury and Brill (1978).

Next, each GDI report was analyzed to determine the specific active failures, latent failures, and local triggers that contributed to the incident. A scenario was then developed for each hazard pattern, illustrating the common factors between all of the incidents. Each of these was also summarized as an event tree illustrating how each of the latent failures contributed to the final damage event. This form of analysis, which has much in common with Fault Tree Analysis, was originally developed by CNRS in France (Monteau, 1977). The scenarios developed for each hazard pattern are given in Table 1 with their frequencies.

Table 1. GDI Hazard Patterns

Hazard Pattern	Number of Incidents			% of Total
1. Aircraft is Parked at the Hangar/Gate/Tarmac	81			**62**
1.1 Equipment Strikes Aircraft		51		39
1.1.1 Tools/Materials Contact Aircraft			4	3
1.1.2 Workstand Contacts Aircraft			23	18
1.1.3 Ground Equipment is Driven into Aircraft			13	10
1.1.4 Unmanned Equipment Rolls into Aircraft			6	4
1.1.5 Hangar Doors Closed Onto Aircraft			5	4
1.2 Aircraft (or Aircraft Part) Moves to Contact Object		30		23
1.2.1 Position of Aircraft Components Changes			15	12
1.2.2 Center of Gravity Shifts			9	7
1.2.3 Aircraft Rolls Forward/Backward			6	4
2. Aircraft is Being Towed/Taxied	49			**38**
2.1 Towing Vehicle Strikes Aircraft		5		4
2.2 Aircraft is Not Properly Configured for Towing		2		2
2.3 Aircraft Contacts Fixed Object/Equipment		42		32
2.3.1 Aircraft Contacts Fixed Object/Equipment			13	10
2.3.2 Aircraft Contacts Moveable Object/Equipment			29	22
Totals	130	130	130	100%

In a similar way, the latent failures were categorized into a second hierarchy in Table 2.

Table 2. Incidence of Latent Failures

SHELL Model Category	Latent Failure	Number of Incidents			% of Total
Hardware				**72**	**27**
H1	**Poor Equipment**		**72**		**27**
	H1.1 Poor Equipment: Inappropriate for Task	39			**15**
	H1.2 Poor Equipment: Mechanical Problem	33			**12**
Environment				**51**	**19**
E1	**Inadequate Space**		**30**		**11**
	E1.1 Inadequate Space: Congested Area	22			**8**
	E1.2 Inadequate Space: Ill-suited for Task	8			**3**
E2	**Problems with Painted Guidelines**				**8**
	E2.1 Guidelines: Do Not Exist	7			**3**
	E2.2 Guidelines: Do Not Extend Out of Hangar	4	**21**		**1**
	E2.3 Guidelines: Not Suitable for Aircraft	10			**4**
Liveware (Individual)				**34**	**13**
LI	**Lack of Awareness of Risks/Hazards**		**34**		**13**
Liveware - Liveware				**108**	**41**
LL1	**Poor Communication**		**29**		**11**
	LL1.1 Poor Communication: Between Crew	24			**9**
	LL1.2 Poor Communication: Between Shifts				
	Personnel Unaware of Concurrent Work	5			**2**
	Correct Number of People Not Used				
LL2	**Pressures to Maintain On-Time Departures**		**8**		**3**
LL3	**Pushback Policies Not Enforced**		**36**		**14**
LL4			**19**		**7**
LL5			**16**		**6**
	Total			**265**	**100%**

Note: Totals exceed the number of incidents due to multiple latent failures per incident.

After consistent latent failures were identified, a logical structure was imposed using ICAO's SHELL Model (ICAO, 1989). For the tasks leading to ground damage, no software failures (e.g. documentation design) were found. Note that there are typically multiple latent failures for each hazard pattern, so that their total is 215 rather than 130.

Next, a cross-tabulation was made of the hazard patterns and overall latent failures to give the results in Table 3.

Table 3. Chi-Square Analysis of the Hazard Patterns/Latent Failure Relationship
*** Indicates a frequency larger than expected**

	HP 1: Aircraft Parked	HP 1.1: Equipment Strikes Aircraft	HP 1.2: Aircraft (or Component) Moves to Contact Object	HP 2: Aircraft Being Towed/Taxied	HP 2.3: Aircraft Contacts Equipment
Hardware	53*	47*	6	19	11
Environment	20	18	2	31*	31*
Liveware (Individual)	22	10	12*	12	9
Liveware-Liveware	62	4	31*	46	40

This data table was tested using a Chi-Square test and found a significant relationship ($X^2_3 = 15.2$, $p < 0.001$). Further analysis using standardized residents gave the over-represented cells (denoted by * in Table 3). These show, for example, that if the aircraft is parked, hardware latent failures are over-represented (HP1) and that

most of this relationship comes from equipment striking aircraft (HP1.1) rather than HP1.2. In fact, this cause was usually poorly-maintained ground equipment striking the aircraft. Similarly, for HP1.2, where the aircraft or a component moved to contact another object, most of the incidents involve people failures (liveware, and liveware-liveware interaction). These were in fact lack of awareness of on-going activities (L-L) or failure to perceive hazards (L).

In this way, a listing could be made of those latent failures associated with each hazard pattern. These in turn defined intervention strategies likely to be successful in prevention of future incidents. Thus, for equipment striking the aircraft (HP1.1) concentrating on maintenance of ground equipment would be a more successful intervention strategy then, for example, improving individual motivation or training.

4. Task Analysis-Based Approaches: The earliest approach to analysis of human factors in aviation maintenance was task-analysis-based (Lock and Strutt, 1985). These authors followed classical human reliability analysis techniques (e.g. Swain, 1990) to break down an aircraft inspection task into successively smaller units of human behavior. Each behavior was then considered for its error potential so that performance shaping factors and interventions could be developed.

In general, task analysis proceeds by progressive redescription of the whole task into successively smaller units. Thus, the overall task may be "check tire pressures and condition." If the aircraft has six tires, then the pressure and condition of each must be checked. For the left nosewheel (for example), the outer surface and bead must be examined for a series of defects (tread wear, de-lamination, cuts, etc.), and so on. When each step is described in sufficient detail, the task description is complete and task analysis can begin (e.g. Drury, Paramore, Van Cott, Grey, and Corlett, 1987). In task analysis, task demands are compared with expected human capabilities to determine potential human/ system mismatches. These in turn define error-prone steps so that countermeasures can be developed. This technique was used as part of the structuring of the FAA's Human Factors in Aviation Maintenance and Inspection Program, beginning with analysis of many inspection tasks (Drury, Prabhu and Gramopadhye, 1990). From these came a set of generic functions (logically-related groups of tasks) for inspection, that were later expanded to cover both inspection and maintenance (Drury, Shepherd and Johnson, 1997). These tasks are defined in Table 4.

Table 4. Generic Function and Task Descriptions of Maintenance and Inspection

Maintenance		Inspection	
Function	**Tasks**	**Function**	**Tasks**
Initiate	Read and understand workcard. Prepare equipment, collect and inspect supplies.	**Initiate**	Read and understand workcard. Select and calibrate equipment.
Site Access	Locate and move to worksite with equipment, parts and supplies.	**Site Access**	Locate and move to worksite.
Part Access	Remove items to access parts, inspect and store items.		
		Search	Move eyes or probe across area, stop if any indication.
Diagnosis	Follow diagnostic procedures. Determine parts to replace/ repair and collect/ inspect needed parts/ supplies.	**Decision**	Re-examine area of indication. Evaluate indication against standards to decide if defective.
Replace/ Repair	Remove parts to be replaced/ repaired, repair and replace.		
Reset Systems	Add supplies/ fluids. Adjust systems to specifications, inspect and buyback if needed.		
Close Access	Refit and adjust items removed for access. Remove equipment parts and unused supplies.		
Respond	Write up documentation on repair.	**Respond**	Write up documentation for repair. Mark defect for repair. Return to search.
BuyBack	(performed by inspector)	**BuyBack**	Examine repair against standards and sign off.

The FAA/AAM program has used FAA researchers, human factors practitioners and airline partners to develop and test systems, procedures, job aids and computer tools designed to ease the utilization of human factors/ ergonomics knowledge within aviation maintenance and inspection. We have developed an application methodology in which each individual project teams a researcher with an airline partner. Most of the major air carriers in the USA have now taken part in these projects. Projects have included design of computer-based training programs, design of enhanced maintenance documentation, development of human factors audit programs, and applications of concepts such as team training and group situation awareness to maintenance. The tools and job aids developed on these projects have been made available to the aviation industry, initially on CD-ROM but more recently on the World Wide Web.

A good overview of the program is given in Latorella and Prabhu (2000). Interventions have been proposed, researched and developed for many of the functions in Table 4. A classification of these (up to 1997) is given in Table 5 from Drury, Shepherd and Johnson (1997). Note that these are also system-level actions such as the development of Crew Resource Management (CRM) training for maintenance, now characterized as Maintenance Resource Management (MRM) (see Taylor and Christensen, 1998). Currently, training of maintenance personnel in human factors concepts is the most popular intervention for maintenance human error. Indeed, such training is now mandated by the International Air Transport Association (IATA) and by the regulatory authorities in many countries.

Table 5. Classification of Interventions for Human Factors in Maintenance and Inspection

System Level Actions	
Development of Human Factors Audit Programs	Characterization of Visual Inspection and NDI
CRM Analysis of Maintenance and Inspection	Error Analysis and Reporting Systems
CRM Training for Maintenance and Inspection	PENS System for Audit
Hangar-Floor Ergonomics Programs	Human Factors Guide

Function-Specific Interventions

Function	Personnel Subsystem	Hardware/SoftwareSubsystem
Initiate Inspection		Workcard redesign
Inspection Access		Restricted space changes
Search	Visual search training	Task lighting design
Decision	Feedback for decision training Individual differences in NDI	
Inspection Response		Computer-based workcards
Initiate Maintenance		
Maintenance Site Access		
Diagnosis	Diagnostic training	ITS computer-based job aid
Maintenance Part Access		
Replace/Repair	International differences	
Reset System		
Inspection Buy-back	International differences	
Close Access		
Maintenance Response		

Here we will explore one intervention in a little more depth, that of improved communication through better document design.

The work documents themselves serve a number of different purposes. First, they are part of a work control system that assures that all tasks are completed according to a time schedule. Assigning a work card to a mechanic, and receiving it back with the stamps and data completed, allows the scheduling system to function reliably. Second, the workcard is part of a quality audit trail which allows management to analyze tasks at a later time if an error was detected. For both reasons, the interactions of mechanics with the work card must

proceed reliably for the system to function correctly. Finally, the work card is a job aid in the Human Factors sense of a tool used to help reliable performance of a procedure. Any human/work card mismatches in this final sense will compromise the overall system reliability. Thus, it is vitally important that the work card be designed to meet user needs, i.e. it must fit the mechanic or inspector.

From previous research, we have found that well-designed documents have a significant impact on performance reliability. Our work has focused on layout rather than content, but has included studies of Simplified English, order of steps, typography, and computer-presented documents (Patel et al 1994). We have also shown how the process for writing and changing documents using user teams can lead to improvements. Two examples are worth mentioning.

First, an existing airline procedure that had caused operational problems was analyzed (Drury, 1998). This document required 9 inspector responses, and had yielded an error rate of 1.5% of responses, meaning that 21% of all documents contained at least one error. When we compared the errors to Human Factors guidelines for good document design, we found that the error rate was 2.5% where these guidelines were violated, and 0.0% where they were met. That is, ALL of the errors could have been eliminated by following good Human Factors practices.

Second, a study of repair station errors (Drury, Kritkauski and Wenner, 1998) compared comprehension of work documents used by two different airlines with those designed using our Documentation Design Aid (DDA). Significant differences in comprehension errors were found between the three formats on two different tasks:

	Cable Workcard	**Wing Workcard**
	Errors	Errors
Airline A Format	52%	36%
Airline B Format	27%	20%
Documentation Design Aid	4%	17%

Thus, the design of work documents DOES impact reliability. It is not just a matter of designing to please operators, or meeting arbitrary style rules, but of using evaluated data to improve the probability that a document will be used correctly in practice. This issue of improved design is relatively simple to incorporate into procedure work cards.

These documentation design rules have been incorporated into a Documentation Design Aid (Drury, 2000) that provides both rule-based advice and knowledge-based reasons for formatting and wording improvements to documents. The DDA program for Windows is available for downloading from hfskyway.faa.gov.

5. Conclusions: This paper provides only a sampling of the research performed and products made available from human factors in aviation maintenance and inspection research programs. The first issue in developing a human factors program in an airline or other maintenance organization is to recognize that human error will not be eliminated by blame, motivation or even most training. True system interventions require an integrated approach of all the elements in the SHELL system: software, hardware, environment, liveware and liveware/ liveware interaction. Organizations should now have sufficient data and incentive to undertake human factors programs. This paper gives a logical approach to error reduction, combining error investigation and task analysis-based approaches.

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